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Indian Standard
METHODS FOR DETERMINING SYNCHRONOUS MACHINE QUANTITIES FROM TESTS

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Indian Standard

METHODS FOR DETERMINING SYNCHRONOUS MACHINE QUANTITIES FROM TESTS

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METHODS FOR DETERMINING SYNCHRONOUS MACHINE QUANTITIES FROM TESTS

0. FOREWORD

0.1 This Indian Standard was adopted by the Indian Standards Institution on 2 February 1974, after the draft finalized by the Rotating Machinery Sectional Committee had been approved by the Electrotechnical Division Council.

0.2 This standard shall be read in conjunction with IS : 7132 - 1973* to which reference has been made for some tests in this standard.

0.3 It is not intended that this standard should be interpreted as requiring the carrying out of any or all of the tests described therein on any given machine. The particular tests to be carried out shall be subject to a special agreement.

0.4 While the tests also apply in general to brushless machines, certain variations do exist and special precautions shall be taken.

0.5 In preparing this standard, assistance has been derived from the following publications:

IEC Publication 34-4 (1967) Rotating electrical machines, Part 4: Methods for determining synchronous machine quantities from tests. International Electrotechnical Commission.

IEEE 115 Test procedures for synchronous machines. Institution of Electrical and Electronic Engineers, USA.

CSN 350201 Testing synchronous machines, Úřad pro normalizaci a měření (Czechoslovakia).

1. SCOPE

1.1 This standard lays down methods for determining characteristics quantities from tests of three-phase synchronous machines having ratings of 1 kVA and above and frequency from 15 to 400 Hz.

1.1.1 The test methods are not intended to apply to special synchronous machines, such as permanent-magnet field machines, inductor type machines, etc.

---

*Guide for testing synchronous machines.

NOTE — For single-phase machines or polyphase machines other than three-phase, modifications will be needed in some cases, but they can usually be readily determined.

2. TERMINOLOGY

2.0 For the purpose of this standard, the definitions given in IS : 1885 (Part XXXV) - 1973* shall apply.

3. GENERAL

3.1 Tests for determining synchronous machine quantities shall be conducted on a completely sound machine, all the devices for automatic regulation being switched off. Unless otherwise stated, the tests are conducted at the rated speed.

3.2 Indicating measuring instruments and their accessories, such as measuring transformers, shunts and bridges used during tests, unless otherwise stated, shall have an accuracy class not inferior to 1·0 (*see* IS : 1248 - 1968†).

The instruments used for determining dc resistances shall have an accuracy class not inferior to 0·5.

The oscillographic measuring equipment shall be chosen with due regard to the rated frequency of the machine to be tested, so that the readings are taken in a linear portion of the vibrator amplitude against frequency characteristic. The measurement of the speed of rotation of synchronous machine may be conducted by means of a stroboscopic method or by using tachometers (mechanical or electrical).

Instead of measuring the speed of rotation, it is permissible to measure frequency by means of a frequency meter when the machine is running synchronous with any other machine or running on its own.

3.3 The temperature of the windings is measured in those tests when the quantities to be determined depend on it or when knowledge of it is required by the safety considerations of the machine during tests.

In cases where transient temperatures may exceed the safe values, the tests shall be started only after the machine has been run at no-load with normal cooling or has been at rest for a period to assure low starting temperature, and the temperatures shall be carefully monitored or predetermined so that the test may be discontinued before the temperature becomes excessive.

3.4 During the test, the winding connections of the machine shall be the same as for normal working.

All quantities are determined with star connection of the armature winding as the basis (unless special connections, such as open delta, are specified). If the armature winding is actually delta connected, the values of the quantities obtained in accordance with this standard shall correspond to an equivalent star-connected winding.

---

*Electrotechnical vocabulary: Part XXXV Rotating machines.

†Specification for direct acting electrical indicating instruments (*first revision*).

3.5 Unless otherwise specified, all the quantities and characteristics shall be designated in per unit values considering rated values of the voltage U_n, and the apparent power S_n as base ones. In this case base current will be:

$$I_n = \frac{S_n}{\sqrt{3}U_n} \text{ amperes}$$

and base impedance

$$Z_n = \frac{U_n^2}{S_n} = \frac{S_n}{3\,I_n^2} \text{ ohms}$$

Similarly the base frequency is regularly selected as equal to rated frequency and from this value base electrical angular velocity ω_n and base time t_n, if needed, are obtained from the equations given below:

$$\omega_n = 2\,\pi f_n \text{ radians per second}$$

$$t_n = \frac{1}{f_n} = \frac{2\pi}{\omega_n} \text{ seconds}$$

A time constant given in seconds may be converted to per unit by dividing it by t_n.

3.5.1 The intermediate calculations, if it is convenient, may be performed in physical values with subsequent conversion to the quantity in per unit value.

3.5.2 The time shall be expressed in seconds.

3.5.3 For calculations of characteristics, and when drawing diagrams, the excitation current corresponding to the rated voltage on the no-load saturation curve shall be taken as its base value.

3.5.4 If a machine has several rated values, those taken for the base values shall be stated.

3.5.5 Small letters designate the quantities in per unit values, and capital letters designate them in physical values.

3.6 Unless otherwise stated, the positive sequence armature resistance is considered to be negligible in the formulae specified for determining synchronous machine reactances.

When the positive sequence armature resistance constitutes more than 20 percent of the measured reactance, the formulae shall be considered as approximate.

3.7 The definitions of the majority of quantities and their experimental methods of determination correspond to the widely accepted two-axis theory of synchronous machines with approximate representation of all circuits, additional to the field winding and stationary circuits relative to it, by two equivalent circuits, one along the direct axis and the other along the quadrature axis, neglecting armature resistance or taking it into consideration only approximately.

As a consequence of this approximate machine representation, three reactances (synchronous, transient and sub-transient) and two time constants (transient and sub-transient) along the direct axis, two reactances (synchronous and sub-transient) and one time constant (sub-transient) along the quadrature axis and the armature short-circuit time constant are considered for transient phenomena studies.

Those time constants are based on the assumption of an exponential decrease of the particular components of quantities involved (currents, voltages, etc). If the plot of the measured component under consideration does not decrease as a pure exponential, for example, in case of a solid rotor machine, the time constant shall normally be interpreted as the time required for component to decrease to $1/\epsilon \approx 0{\cdot}368$ of its initial values. Exponential decay curves corresponding to these time constants shall be considered as equivalent curves replacing the actual measured ones.

3.8 Synchronous machine quantities vary with saturation of the magnetic circuits. In practical calculations both saturated and unsaturated values are used.

Unless otherwise stated, the saturated value of a reactance shall be taken as the rated (armature) voltage value of the quantity, and their unsaturated value shall be taken as the rated (armature) current value, except synchronous reactance which is not defined as saturated.

The rated (armature) voltage value of a quantity corresponds to the magnetic condition of the machine during sudden short-circuit of the armature winding at no-load rated voltage, the machine running at rated speed.

The rated (armature) current value of a quantity corresponds to the condition in which the fundamental ac component of armature current which determines this particular quantity is equal to the rated current.

4. METHODS OF DETERMINATION

4.1 Methods for determining synchronous machine quantities are given in Table 1.

TABLE 1 METHODS OF DETERMINATION OF SYNCHRONOUS MACHINE QUANTITIES

(*Clause* 4.1)

QUANTITY	METHOD OF DETERMINATION	CLAUSE No.	SATURATED OR UNSATURATED VALUE	REMARKS
(1)	(2)	(3)	(4)	(5)
X_d	a) No-load saturation and sustained three-phase short-circuit tests	5.1.2	Unsaturated	Preferred
	b) Low slip test	5.5, 5.6	Unsaturated	Preferred
K_c	No-load saturation and sustained three-phase short-circuit tests	5.1.3	—	—
X_q	a) Negative excitation test	5.4, 5.4.1	Saturated Unsaturated	Preferred
	b) Low slip test	5.5, 5.6	Unsaturated	Preferred
	c) On-load test by measuring the load angle	5.7, 5.8	Saturated	—
X'_d	a) Sudden three-phase short-circuit test	5.9, 5.10	Unsaturated Saturated	Preferred
	b) Voltage recovery test	5.11, 5.12	Unsaturated	—
	c) Calculation from the test values of X_d, τ' and τ'_d	5.40.1	—	—
X''_d	a) Sudden three-phase short-circuit test	5.9, 5.10.2	Unsaturated Saturated	Preferred
	b) Voltage recovery test	5.11, 5.12.2	Unsaturated	—
	c) Applied voltage test with the rotor in direct and quadrature-axis positions with respect to the armature winding field axis	5.13, 5.14	Unsaturated Saturated	These may be used for the unsaturated value of X''_d, but are usually not practicable for the saturated value because of the large current required and possible overheating of solid parts
	d) Applied voltage test with the rotor in any arbitrary position	5.15, 5.16	Unsaturated Saturated	
	e) Test conducted by disconnecting the machine running close to synchronous speed from a three-phase reduced voltage supply	5.17	Unsaturated Saturated	

(*Continued*)

TABLE 1 METHODS OF DETERMINATION OF SYNCHRONOUS MACHINE QUANTITIES — *Contd*

QUANTITY	METHOD OF DETERMINATION	CLAUSE No.	SATURATED OR UNSATURATED VALUE	REMARKS
(1)	(2)	(3)	(4)	(5)
X''_q	a) Applied voltage test with the rotor in direct and quadrature-axis positions with respect to the armature winding field axis	5.13, 5.14	Unsaturated Saturated	Both these methods are practically equivalent and may be used to determine unsaturated value. These methods are usually not practicable for the determination of the saturated value because of the large current required, and possible overheating of solid parts
	b) Applied voltage test with the rotor in any arbitrary position	5.15, 5.16.2	Unsaturated Saturated	
X_2	a) Line-to-line sustained short-circuit test	5.18, 5.19	Unsaturated	Preferred
	b) Negative-phase sequence test	5.20, 5.21	Unsaturated	—
	c) Calculation from the test values of x''_d and x''_q	5.40	—	—
R_2	a) Line-to-line sustained short-circuit test	5.18, 5.19	Unsaturated	Preferred
	b) Negative-phase sequence test	5.20, 5.21	Unsaturated	—
X_0	a) Single-phase voltage application test to the three-phase connected in series (an open delta) or parallel	5.22, 5.23	Unsaturated	Preferred
	b) Line-to-line and to neutral sustained short-circuit test	5.24, 5.25.1	Unsaturated	—

(*Continued*)

TABLE 1 METHODS OF DETERMINATION OF SYNCHRONOUS MACHINE QUANTITIES — *Contd*

QUANTITY	METHOD OF DETERMINATION	CLAUSE No.	SATURATED OR UNSATURATED VALUE	REMARKS
(1)	(2)	(3)	(4)	(5)
R_0	a) Single-phase voltage application test to the three-phase connected in series (an open delta) or parallel	5.22, 5.23	—	Preferred
	b) Line-to-line and to neutral sustained short-circuit test	5.24, 5.25.2	—	—
X_p	a) No-load saturation sustained three-phase short-circuit and over-excitation test at zero power-factor	5.2.3	—	—
	b) Calculation from the test value of X_a measured	5.2.4	—	—
Armature winding direct current resistance (R_a)	Ammeter-voltmeter method and bridge method	8.2, 8.3 of IS: 7132-1973*	—	—
Excitation winding direct current resistance (R_f)	Ammeter-voltmeter method or bridge method	8.2, 8.3 of IS: 7132-1973*	—	—
R_1	Calculation of positive sequence armature winding resistance	5.40.3	—	—

*Guide for testing synchronous machines.

(*Continued*)

TABLE 1 METHODS OF DETERMINATION OF SYNCHRONOUS MACHINE QUANTITIES — *Contd*

QUANTITY	METHOD OF DETERMINATION	CLAUSE NO.	SATURATED OR UNSATURATED VALUE	REMARKS
(1)	(2)	(3)	(4)	(5)
τ'_{do}	a) Field current decay test with armature winding open circuited	5.26, 5.27	—	Preferred
	b) Voltage recovery test	5.11, 5.12.3	—	—
	c) Calculation from the test values of x_d, x'_d and τ'_d	5.40.1	—	—
τ'_d	a) Sudden three-phase short-circuit test	5.9	—	If a sudden short-circuit test is performed for determining x'_d then τ'_d shall be determined from the same test. In all other cases preference is given to the field current decay method with the armature winding short-circuited
	b) Field current decay test with armature winding short-circuited	5.29	—	
	c) Calculation from the test values of x_d, x'_d and τ'_{do}	5.40.1	—	
τ''_{do}	Voltage recovery test	5.11, 5.12.3	—	—
τ''_d	Sudden three-phase short-circuit test	5.9, 5.10.4	—	—
τ_a	a) Sudden three-phase short-circuit test:	5.9		
	i) By decrease of the periodic (ac) component in the excitation winding current	5.10.5	—	Preferred
	ii) By decrease of the aperiodic (dc) components of the current in the armature winding phases	5.10.6	—	—
	b) Calculation from the test values of x_2 and r_a	5.40.4	—	—

(*Continued*)

TABLE 1 METHODS OF DETERMINATION OF SYNCHRONOUS MACHINE QUANTITIES — *Contd*

QUANTITY (1)	METHOD OF DETERMINATION (2)	CLAUSE No. (3)	SATURATED OR UNSATURATED VALUE (4)	REMARKS (5)
τ_j	a) Suspended rotor oscillation test	5.30, 5.31	—	The application of one or another method depends on the design and the apparent power of the machine under test
	b) Auxiliary pendulum swing test	5.32, 5.33	—	
	c) No-load retardation test	5.34, 5.35	—	
	d) On-load retardation test with synchronous machine operating as a motor	5.36, 5.37	—	
	e) Acceleration after a load drop test with machine operating as a generator	5.38, 5.39	—	
H	a) Suspended rotor oscillation test	5.30, 5.31	—	The application of one or another method depends on the design and the apparent power of the machine under test
	b) Auxiliary pendulum swing test	5.32, 5.33	—	
	c) No-load retardation test	5.34, 5.35	—	
	d) On-load retardation test with synchronous machine operating as a motor	5.36, 5.37	—	
	e) Acceleration after a load drop test with machine operating as a generator	5.38, 5.39	—	
i_{fn}	a) Direct measurement during operation under rated conditions	6.2	—	Preferred
	b) Phasor diagrams:			
	Potier	6.3	—	—
	ASA	6.4	—	—
	Swedish	6.5	—	—
ΔU_n	a) Direct measurement	7.1	—	—
	b) By diagram from the no-load saturation characteristic and known i_{fn}	7.2	—	—

NOTE — The details for calculating per unit values from the physical values of some of the synchronous machine quantities are also given in the relevant clauses of the standard mentioned in this table.

5. DESCRIPTION OF THE TESTS AND DETERMINATION OF QUANTITIES

5.1 Determination of Quantities from the No-Load Saturation and Sustained Three-Phase Short-Circuit Characteristics

5.1.1 The no-load saturation characteristic and sustained three-phase short-circuit characteristic are determined in accordance with IS : 7132-1973*.

5.1.2 *Direct-Axis Synchronous Reactance* (X_d) — Direct-axis synchronous reactance is determined from the no-load saturation and three-phase sustained short-circuit characteristics as a quotient of the no-load voltage taken from the air-gap line at some excitation and the sustained short-circuit current value taken from the short-circuit characteristic at the same excitation current (*see* Fig. 1) :

$$X_d = \frac{U_n}{\sqrt{3}\, I} \text{ ohms}$$

$$X_d = \frac{u_n}{i} = \frac{AC}{BC} = \frac{i_{fk}}{i_{fg}} \text{ per unit}$$

The value of X_d determined as above corresponds to an unsaturated state of the machine.

5.1.3 *Short-Circuit Ratio* (K_c) — Short-circuit ratio is determined from the no-load saturation and three-phase sustained short-circuit characteristics as quotient of the excitation current corresponding to the rated voltage on the no-load saturation curve and the excitation current corresponding to the rated current on the short-circuit curve (*see* Fig. 1) :

$$K_c = \frac{OD}{OH} = \frac{i_{fo}}{i_{fk}}$$

5.2 Determination of Potier Reactance (X_p)

5.2.1 The Potier reactance is determined graphically from the no-load, three-phase sustained short-circuit and overexcited zero power-factor characteristics. In case the complete overexcited zero power-factor characteristic is not available, the excitation current corresponding to the rated voltage and rated armature current, at zero power-factor (overexcited) is sufficient.

5.2.2 Zero power-factor characteristic is determined in accordance with **21** of IS : 7132-1973*.

5.2.3 The point *A* of Fig. 2 corresponds to the excitation current at rated voltage, rated armature current and zero power-factor overexcited.

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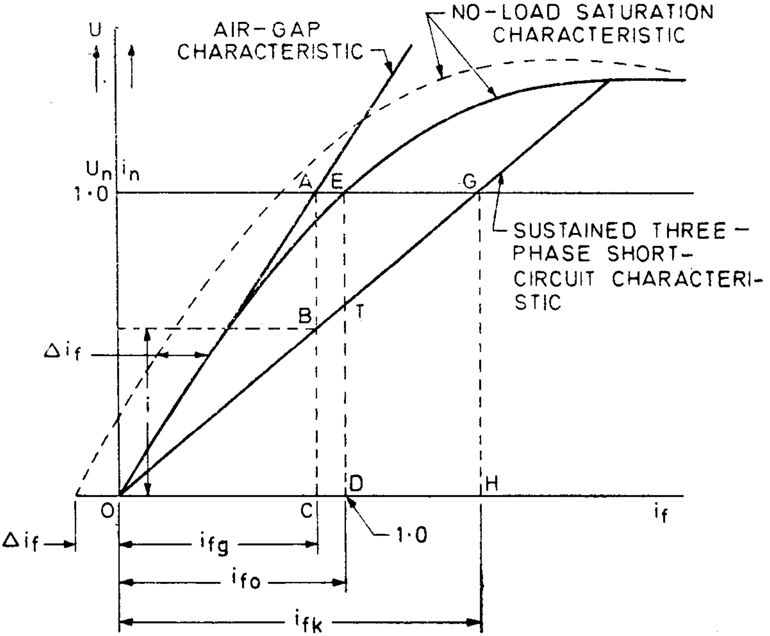


FIG. 1 NO-LOAD SATURATION AND SUSTAINED THREE-PHASE SHORT-CIRCUIT CHARACTERISTICS

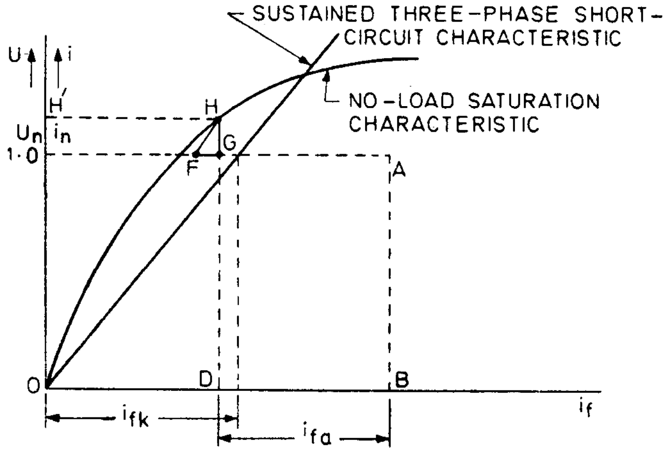


FIG. 2 DETERMINATION OF POTIER REACTANCE

To the left from the point A and parallel to the abscissa, length AF equal to the excitation current (i_{fk}) for the rated armature sustained short-circuit current is laid off. The line parallel to the initial lower portion of the no-load characteristic is drawn through the point F up to the intersection with upper part of the no-load characteristic (point H). The length of perpendicular from the point H to point G (intersection with AF line) represents the Potier reactance drop at the rated armature current. In per unit value X_p is equal to HG.

5.2.4 Potier reactance can also be calculated from an empirical formula given below:

$$X_p = aX_a$$

where

a = a factor which is equal to 1·0 for salient pole machines and is equal to 0·6 (0·65) for cylindrical rotor machines, and

X_a = total armature reactance without the rotor.

NOTE — In case more precise values of factor a are available from previous experience of machines of similar construction, the same shall be used in the equation of X_p.

5.2.4.1 Total armature reactance (X_a) is determined by applying three-phase voltage at rated frequency to the terminals of the armature winding without the rotor in position. The applied voltage is so chosen that the armature current is within the rated value. Measurements are made of terminal voltage in volts (U), line current in amperes (I) and supplied active power in watts (P) during the test.

X_a is calculated from the equations given below:

$$X_a = \sqrt{Z^2 - R^2} \text{ ohms}$$

$$X_a = \sqrt{z^2 - r^2} \text{ per unit}$$

where

$$Z = \frac{U}{\sqrt{3}\,I} \text{ ohms,}$$

$$z = \frac{u}{i} \text{ per unit,}$$

$$R = \frac{P}{3\,I^2} \text{ ohms, and}$$

$$r = \frac{p}{i^2} \text{ per unit.}$$

5.2.5 Potier reactance can also be determined partly by test and partly by calculation in cases where it is not possible to determine experimentally even the excitation current corresponding to rated armature current at zero power-factor and rated voltage.

The excitation current i_k, corresponding to rated armature current, is determined according to sustained three-phase short-circuit characteristic. The excitation current component i_a, compensating the armature reaction only at rated current, is calculated from machine parameters.

The difference of current $(i_k - i_a)$ is plotted on the *x*-axis as *OE* (*see* Fig. 3). From the point *E* perpendicular is drawn to intersect the no-load characteristic at *F*.

The calculated Potier reactance is given by:

$$X_p = EF$$

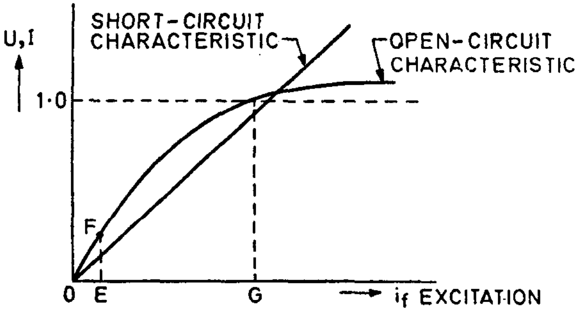


FIG. 3 ALTERNATIVE METHOD FOR DETERMINATION OF POTIER REACTANCE

5.3 Measurement of Armature Bore Leakage Reactance (X_b) Without the Rotor in Position

5.3.1 The armature is supplied with a three-phase voltage at its rated frequency. The voltage is so chosen that the armature current is near the rated value. Under these test conditions, the emf (U_c) induced in a search coil placed in the armature bore, as detailed below, is measured.

The search coil is placed on the active surface of stator (in stator bore), length of coil shall be equal to full length of stator core and its width equal to pole pitch. Active sides of this coil are fastened above the slot wedges and over-hangs are stretched out by braces along the radii towards the machine axis in planes, limiting the stator core packets for protecting them from the influence of leakage fluxes around the over-hang parts of the winding.

The current in all the three phases is also measured and a mean value is determined. The armature bore leakage reactance (X_b) is then calculated from the following equation:

$$X_b = \frac{K_w \, T_{ph} \, U_c}{I \, T_c} \left(1 + \frac{R_c}{R_v}\right)$$

where

X_b = armature bore leakage reactance in ohms,

K_w = armature winding factor which is a product of spread factor and pitch factor and is computed in the usual manner,

I = mean armature phase current in amperes,

U_c = voltage across the terminals of the search coil in volts at the current I,

T_{ph} = number of series turns per phase of the armature winding,

T_c = number of turns in the search coil,

R_c = resistance of the search coil in ohms, and

R_v = resistance in ohms of the voltmeter used.

If the stator (armature) has fractional number of slots per pole per phase, then the width of the search coil is made equal to largest whole number of slots included in a pole pitch and X_b is calculated as per the formula :

$$X_b = \frac{K_w T_{ph} U_c}{I T_c \operatorname{Sin}\left(\frac{N}{3_q}\right)} \left(1 + \frac{R_c}{R_v}\right)$$

where

N = largest whole number of slots included in a pole pitch, and

q = fractional number of slots per pole per phase = 3·14.

5.3.2 Armature leakage reactance (X) is determined from the following equation :

$$X = X_a - X_b$$

where

X_a = total armature reactance determined according to **5.2.4.1**, and

X_b = armature bore leakage reactance determined in accordance with **5.3.1**.

5.4 Negative Excitation Test — The test is conducted with the machine operating under no-load in parallel with the network. The excitation current is steadily reduced to zero, its polarity reversed, and it is then increased up to the moment when the machine begins to slip. The values of the voltage, armature current and excitation current are measured during the test up to the moment when the machine begins to slip.

5.4.1 *Determination of X_q from the Negative Excitation Test* — The determination of X_q from the negative excitation test is made using the formula (in per unit or physical values) :

$$x_q = x_d \times \frac{u_r}{u_r + e}$$

where

x_d = direct-axis synchronous reactance determined from the same straightened no-load saturation characteristic,

u_r = voltage at the moment of slipping, and

e = no-load emf for the excitation current i_{fr} at which the machine slips. It is determined from the straightened no-load saturation characteristic drawn through the point corresponding to the voltage at the moment of slipping (Fig. 4).

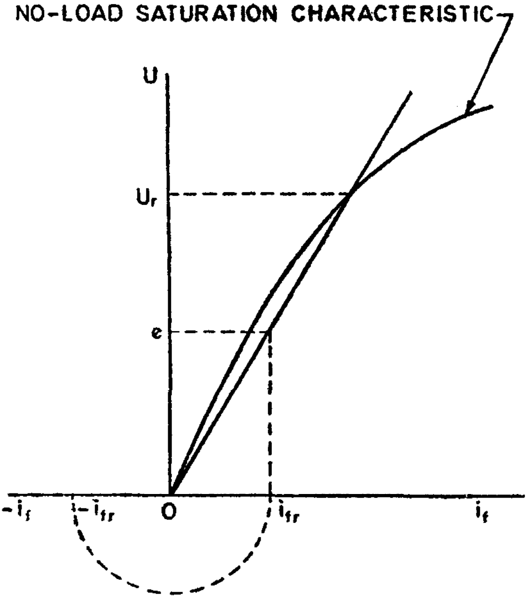


FIG. 4 QUADRATURE-AXIS SYNCHRONOUS REACTANCE FROM NEGATIVE EXCITATION TEST

If during the test the armature current at which the machine slips (I_r) is measured, X_q is determined using the formulae:

$$X_q = \frac{U_r}{\sqrt{3}\,I_r} \text{ ohms}$$

$$x_q = \frac{u_r}{i_r} \text{ per unit}$$

The value of X_q obtained from this test may, depending upon the value of U_r, include saturation. If it is possible to reduce the applied voltage to 60 percent of the rated value or lower, then the test may be carried out for obtaining unsaturated value of X_q.

5.5 Low Slip Test (*See* **Fig. 5**) — During the low slip test, subnormal symmetrical three-phase voltage (2 to 15 percent of U_n) is applied to the armature terminals of the machine under test. The voltage shall be such that the machine does not pull in. The excitation winding shall be open-circuited, the rotor shall be driven by a prime mover at a slip less than 0·01 and for solid rotor machines much less than that value so that the currents induced in the damper circuits during asynchronous operation shall have negligible influence on the measurements. During switching on and off of the supply, the excitation winding shall be closed (short-circuited or closed through a discharge resistance) to avoid possible damage. Armature current and voltage and the slipring voltage and slip are measured by indicating instruments or recorded by oscillograph. If the residual voltage measured before the test is larger than 30 percent of the supply test voltage, the rotor shall be demagnetized. Demagnetizing may be done, for example, by connecting the field winding to a low-frequency source with current about 50 percent of the no-load rated voltage excitation current of the tested machine and gradually decreasing its amplitude and frequency (the latter, if possible).

The slip may be determined as the ratio of the frequency of voltage induced in the field to the frequency of the applied voltage.

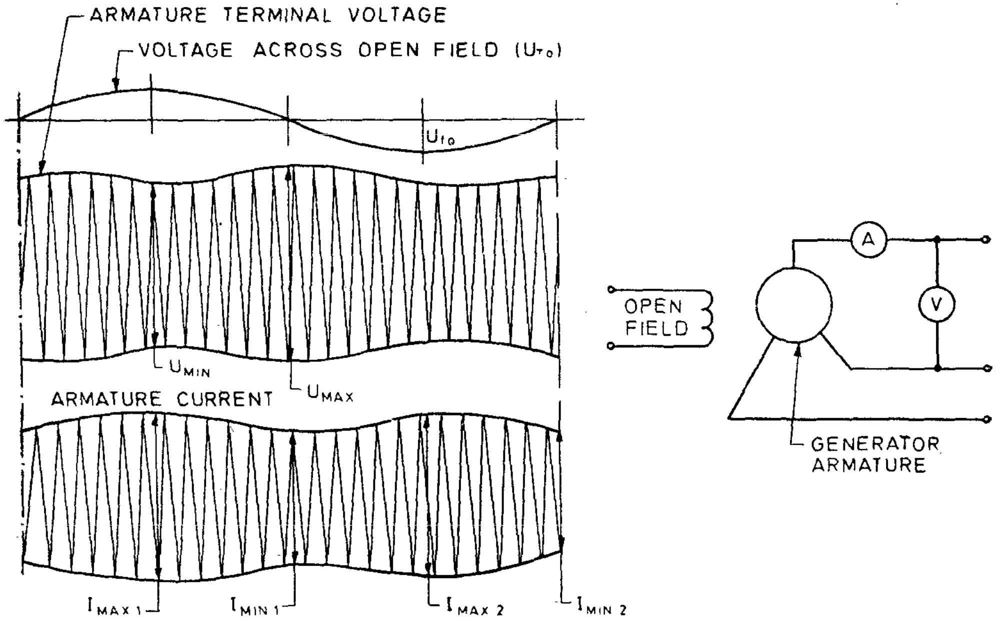


FIG. 5 LOW SLIP METHOD OF OBTAINING QUADRATURE-AXIS SYNCHRONOUS REACTANCE

The slip may also be determined by the use of a stroboscope energized from the same frequency as the applied voltage illuminating equally spaced marks on the rotor, the number of marks being equal to the number of poles. The slip frequency is the apparent rate of progression of the marks in revolutions per second multiplied by the number of pairs of poles, and the slip is the ratio of slip frequency to the frequency of the applied voltage.

5.6 Determination of X_q from the Low Slip Test

5.6.1 To determine X_q from the low slip test, armature current and voltage are measured at maximum excitation winding voltage (U_{fo}), and X_q is calculated using the following formulae:

$$X_q = \frac{U_{min}}{\sqrt{3}\, I_{max}} \text{ ohms}$$

$$x_q = \frac{u_{min}}{i_{max}} \text{ per unit}$$

NOTE — If I_{max} does not coincide with U_{min}, use in calculations I_{max} as a base and its corresponding voltage. If, during the test, the residual voltage of the machine (U_{res}) is in the limits of 10 to 30 percent of the supply test voltage, the value of the current is determined using the formulae:

$$I_{max} = \sqrt{I_{av}^2 - \left(\frac{U_{res}}{\sqrt{3}\, X}\right)^2} \text{ amperes}$$

$$i_{max} = \sqrt{i_{av}^2 - \left(\frac{u_{res}}{x_d}\right)^2} \text{ per unit}$$

where

I_{av} = half sum of the two consecutive maximum of the current envelope curve (*see* Fig. 5).

5.6.2 A check of the measured value may be made by calculating X_d from the same test, using the results of the voltage and current measurements at the time when the voltage of the open-circuit excitation winding is equal to zero and comparing it with its value determined from no-load saturation and sustained three-phase short-circuit tests. Then,

$$X_d = \frac{U_{max}}{\sqrt{3}\, I_{min}} \text{ ohms}$$

$$x_d = \frac{u_{max}}{i_{min}} \text{ per unit}$$

With a residual voltage less than 30 percent of the supply test voltage, the half sum of the two consecutive minima of the envelope curve represents I_{min} (*see* Fig. 5).

5.6.3 The results of X_q measurements from the low slip test may be considered correct only if the value of X_d obtained from this test practically agrees with its value obtained in accordance with **5.1**. Otherwise, the test is repeated at several low values of the slip, followed by extrapolation of X_q values to zero slip. The value of quadrature-axis synchronous reactance obtained from this test practically corresponds to the unsaturated value.

5.7 On-Load Test and Measurement of the Load Angle (δ)

5.7.1 The test is conducted with the machine operating in parallel with the network. The loading of the machine shall not be less than 50 percent of the rated active load at rated power factor.

When conducting the test, armature current (i) and voltage (u), angle ϕ between the voltage and the current (using the two-wattmeter method) and load angle δ (the internal angle between the terminal voltage and emf) are measured. The load angle may be measured by using the stroboscopic method or any other accurate method.

5.7.2 *Measurement of Load Angle (δ) by Stroboscope* — This test is made by noting the shift in rotor position (load angle) when the load is changed from a specified power, power factor, and voltage to no-load with the same specified voltage. The test is made at rated frequency. The shift in rotor position is observed using a stroboscope connected to the armature terminals. The change x, in the position of a point on the rotor, between the two load conditions, is measured as an arc length using a scale. The load angle (δ) in electrical radians, is calculated as follows:

$$\delta = \frac{x}{2}\frac{P}{R} \text{ electrical radians}$$

where

x = change in position of a point on the rotor measured as arc length,

P = number of poles, and

R = radius to the point on rotor where x is measured.

NOTE — x and R shall be in consistent units. Alternatively, a scale which reads directly in electrical radians may be used.

5.8 Determination of X_q from the On-Load Test and Measurement of the Load Angle — X_q is determined by the following formulae:

$$X_q = \frac{U \tan \delta}{\sqrt{3}\, I (\text{Cos}\, \phi - \text{Sin}\, \phi \tan \delta)} \text{ ohms}$$

$$x_q = \frac{u \tan \delta}{i\, (\text{Cos}\, \phi - \text{Sin}\, \phi \tan \delta)} \text{ per unit}$$

5.9 Sudden Three-Phase Short-Circuit Test

5.9.1 This test is conducted at rated speed. The test is made by applying a short-circuit to the armature winding when operating at the desired voltage on no-load. Excitation of the machine is, as a rule, accomplished from its own exciter which shall be separately excited. If its own exciter cannot be used, then a separate exciter may be used, but its rated current value shall be at least twice the no-load field current of the tested machine and its armature resistance not greater than that of the main machine exciter. This exciter shall be separately excited.

5.9.2 Before making these tests the machine shall be carefully inspected to see that the bracing of the stator coil ends is satisfactory, the foundation is in good condition, and the holding down bolts are tight. The rotor shall be inspected to see that all keys and bolts are in place and properly tightened.

Certain precautions are required in preparing the electric connections because of the abnormal conditions which attend a sudden short-circuit test. Very heavy currents flow, particularly in large machines and results in great forces on the test conductors. To prevent damaging movement, test conductors shall be securely braced.

The armature circuit shall be solidly grounded at a single point using a conductor of size comparable to the leads from the machine terminals. There are two choices for the location of this ground connection: the neutral of a *Y*-connected armature winding or the point common to the three contacts of the shorting-circuit breaker. If shunts are used in measuring the currents, their common point shall be where the ground connection is made, to avoid hazardous voltages at the oscillograph in case of a mishap. If current transformers are used in measuring armature current, the point common to their primaries shall be where the ground connection is made, unless they are insulated to withstand full line-to-line armature voltage.

The automatic voltage regulator should be made inoperative. Also all protective relays which may cause the field circuit breaker to trip shall be made inoperative. A discharge resistor of sufficiently low value shall be used so that if the field circuit breaker were to trip, the voltage across the field winding would not be excessively high.

5.9.3 The three phases are to be short-circuited practically simultaneously. The phase contacts shall close within 15 electrical degrees of each other. This value may be exceeded on test when the armature dc component is not of importance.

5.9.4 To measure short-circuit current, use is made of non-inductive shunts, air-cored transformers or suitable current transformers. The latter shall be used in dealing with ac current components only and shall be chosen so that the initial value of the sub-transient component of the short-circuit current is on the straight line portion of the transformer characteristic.

The air-cored transformer is connected to the oscillograph through an integrating amplifier. When it is necessary to determine the maximum aperiodic and periodic values of short-circuit current components only, an integrating oscillographic galvanometer may be used.

The total resistance of the measuring instruments and their leads connected into the secondary circuit of current transformers shall not exceed the rated values accepted for the given type of transformers.

5.9.5 The terminal voltage of the machine, the excitation current and the excitation winding temperature are measured immediately before short-circuiting.

5.9.6 To obtain quantities corresponding to the unsaturated state of the machine, the test is performed at several armature voltage of 10 to 40 percent rated value. The quantities are obtained for each test and plotted against the initial values of ac transient or sub-transient armature currents. From this relationship, the required quantities are obtained at the rated armature current value.

5.9.7 To obtain quantities corresponding to the saturated state of the machine, the test is performed with rated voltage at the terminals of the machine before short-circuiting the armature winding.

If the sudden short-circuit test cannot be performed at rated armature voltage, the tests shall be conducted at several armature voltages (for example, 30 percent, 50 percent and 70 percent of rated armature voltage), and the quantities determined for each test. They are then plotted against open-circuit voltage before short-circuiting and the approximate rated armature voltage quantity is found by the extrapolation method.

In the case of large synchronous machines, it is generally found that the synchronous machine quantities determined from sudden short-circuit tests even at 30 percent of rated armature voltage, correspond very nearly to the saturated state of the machine in all such cases the armature voltage at which the sudden short-circuit is carried out for the purpose of determining synchronous machine quantities corresponding to the saturated state of the machine shall be a matter of agreement between the manufacturer and the customer.

5.9.8 To determine the machine quantities, oscillograms of the armature current in each phase and of the current in the excitation circuit are taken (*see* Fig. 6).

Oscillograph recording shall continue for a time interval not less than $(\tau'd+0{\cdot}2)$ seconds after the short-circuit. The steady state values shall also be recorded by restarting the oscillogram following the establishment of steady state conditions. For a check the final values shall be measured by instruments. Shorter oscillographic records may be taken if it is known from tests on similar machines that the current value decays as an exponential.

5.9.9 The change with time of aperiodic and periodic armature current components in each phase is determined from the three-phase short-circuit oscillograms as an algebraic half-sum and algebraic half-difference of the ordinates of the upper and lower envelopes of the short-circuit current in separate phases respectively.

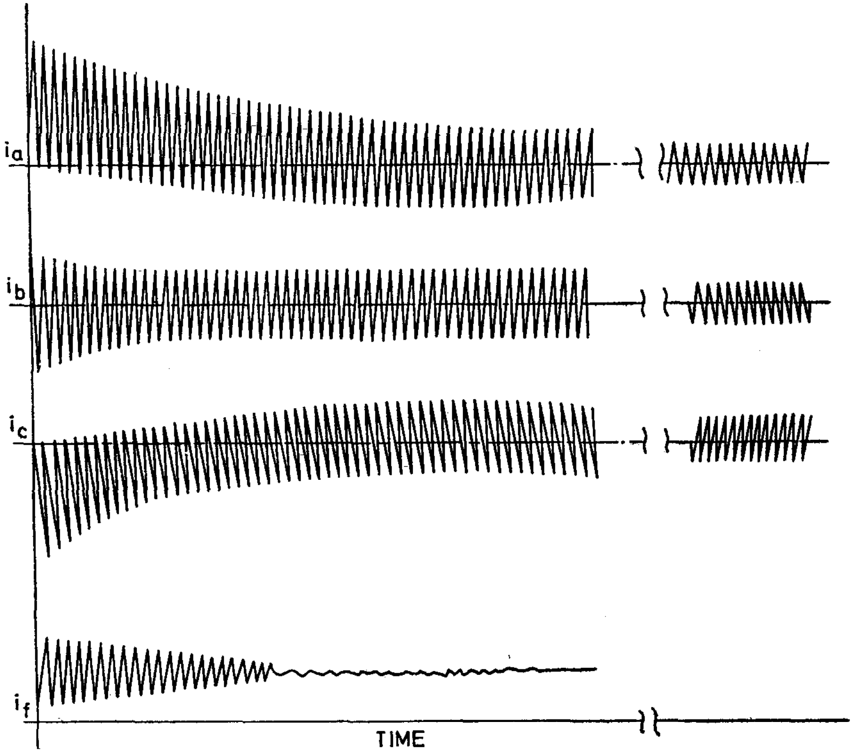


FIG. 6 SUDDEN SHORT-CIRCUIT CURRENTS OF SYNCHRONOUS GENERATOR : ARMATURE CURRENTS, i_a, i_b, i_c AND FIELD CURRENT, i_f

5.9.10 The periodic components of the armature current during sudden short-circuit is determined as a mean arithmetic of the periodic components of the armature current in all the three phases.

5.9.11 To determine the transient ($\triangle i'_k$) and subtransient ($\triangle i''_k$) components, the value of the sustained short-circuit current i (∞) is subtracted from the curve of the periodic component of the armature current. The remainder, which is the sum of $\triangle i'_k$ and $\triangle i''_k$, is plotted on paper with a semilog scale. This plot may be a straight line or a curve.

5.9.11.1 When the latter part of this plot is a straight line (corresponding to an exponential), this line extrapolated to zero time gives the initial value $\triangle i_k$ (0) of the transient component of short-circuit current (*see* Fig. 7).

5.9.11.2 When the latter part of this plot is a curve, the amplitude of the current i_A is measured (*see* Fig. 8) at a time *OA'*, where *OA'* is taken as

0·2 seconds or the time at which subtransient effects become negligible. The time OB' is measured at which the current is $i_B = (1/\epsilon) \triangle i_A$. The time constant τ'_d is taken as $(OB' - OA')$ seconds. The straight line through the values of current i_B and i_A is assumed to represent the equivalent value of $\triangle i_k$ and, when it is extrapolated to zero time, it gives the initial value $\triangle i_k(0)$ of the transient component of short-circuit current.

The subtransient short-circuit current component is defined as the difference between the $\triangle i'_k + \triangle i''_k$ curve and the straight line representing the value of $\triangle i_k$. The variation of the subtransient current component with time is also plotted on the semilog scale (*see* Fig. 7).

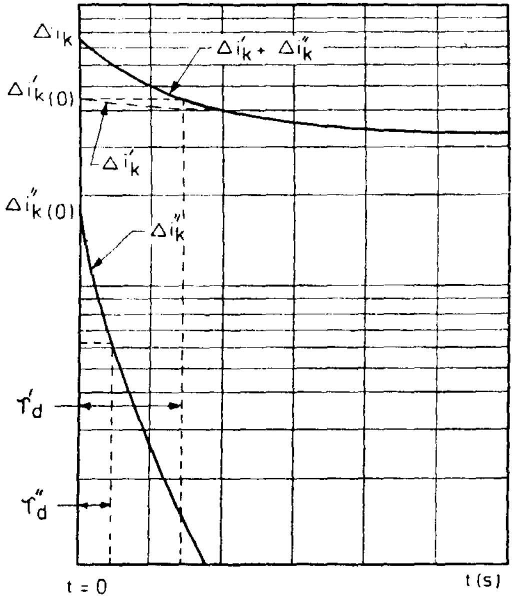


FIG. 7 REACTANCES AND TIME CONSTANTS FROM SUDDEN SHORT-CIRCUIT TEST

5.9.12 The aperiodic current components of all the phases are plotted against time on semilog scale. Extrapolation of these curves to the zero time gives the initial values of the corresponding current (*see* Fig. 9).

5.9.13 To find the greatest possible value of the aperiodic component, the initial values of the aperiodic components of separate phases obtained by extrapolation are laid off as vectors along three radial lines 60° apart, radiating from one origin, the largest of the three vectors being laid off on

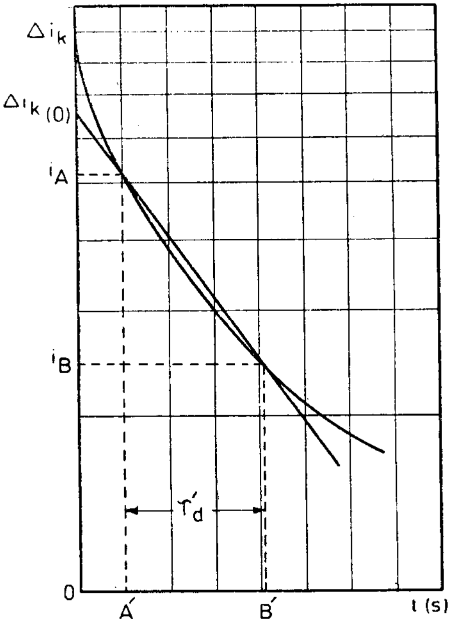


FIG. 8 ALTERNATIVE TO FIG. 7 IF TRANSIENT COMPONENT DECREMENT IS NOT EXPONENTIAL

the middle line. Perpendiculars are drawn through the end of each vector. The vector drawn from the origin to the centre of the triangle formed by the intersections of these perpendiculars represents the largest possible aperiodic component equal to the initial value of the amplitude of the periodic component (*see* Fig. 10).

The largest possible value of the aperiodic component of the current may be determined analytically by the formulae (in per unit or physical values) :

$$i_{a\,\max} = \frac{2}{\sqrt{3}} \sqrt{i_{a2}^2 + i_{a3}^2 - i_{a2}\, i_{a3}}$$

where i_{a3} is the highest initial absolute value of the aperiodic components of the currents and i_{a2} is the absolute initial value of aperiodic current components in either of the other phases.

5.9.14 The function of the periodic component of the excitation current against time is determined from the excitation current oscillogram and is plotted on a semilog scale. Extrapolation of the curve to zero time gives the initial value of the periodic current component.

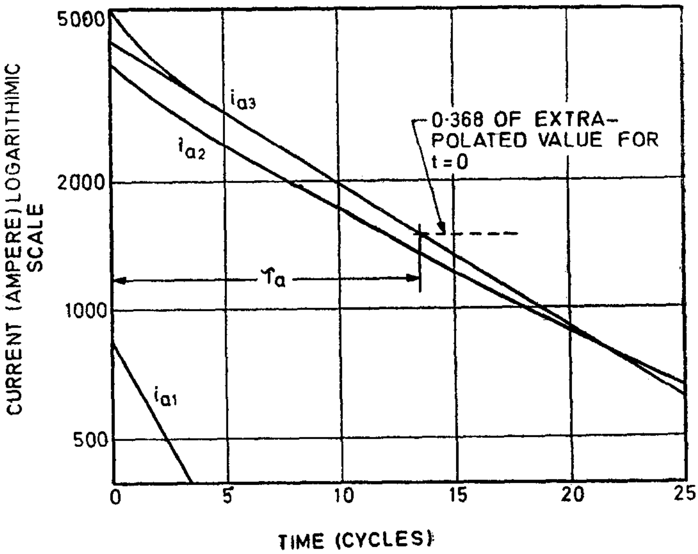


FIG. 9 SEMILOG PLOT OF APERIODIC COMPONENTS OF ARMATURE CURRENTS, i_{a1}, i_{a2}, i_{a3}

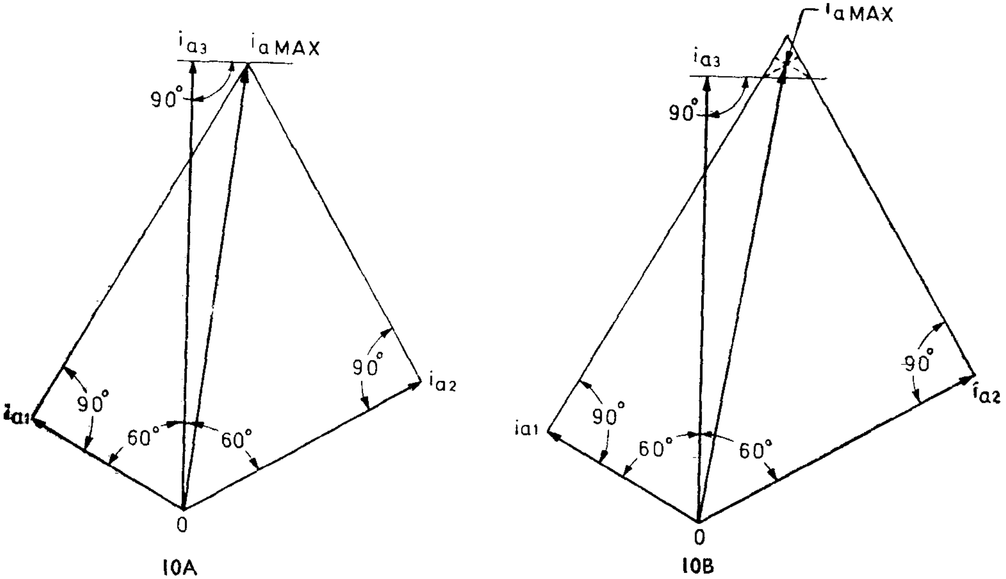


FIG. 10 MAXIMUM APERIODIC COMPONENT OF THREE-PHASE SHORT-CIRCUIT CURRENT

5.10 Determination of Quantities from the Sudden Three-Phase Short-Circuit Test

5.10.1 The direct-axis transient reactance is determined as the ratio of the no-load voltage, measured immediately before the short-circuit [$u(0)$] to the initial value of the periodic component of the short-circuit current neglecting the subtransient component (*see* Fig. 7).

$$X'_{\mathrm{d}} = \frac{U(0)}{\sqrt{3}\,[I(\propto) + \Delta I'_{\mathrm{k}}(0)]} \text{ ohms}$$

$$x'_{\mathrm{d}} = \frac{u(0)}{[i(\propto) + \Delta i'_{\mathrm{k}}(0)]} \text{ per unit}$$

5.10.2 The direct-axis subtransient reactance is determined as the ratio of the no-load voltage, measured immediately before the short-circuit $U(0)$ to the initial value of the periodic component of the short-circuit current, obtained from the analysis of the oscillogram (*see* Fig. 7).

$$X''_{\mathrm{d}} = \frac{U(0)}{\sqrt{3}\,[I(\propto) + \Delta I'_{\mathrm{k}}(0) + \Delta I''_{\mathrm{k}}(0)]} \text{ ohms}$$

$$x''_{\mathrm{d}} = \frac{u(0)}{[i(\propto) + \Delta i'_{\mathrm{k}}(0) + \Delta i''_{\mathrm{k}}(0)]} \text{ per unit}$$

5.10.3 The direct-axis transient short-circuit time constant τ'_{d} is determined as the time required for the transient armature current component to decrease to $1/\epsilon \approx 0{\cdot}368$ of its initial value (*see* Fig. 7 and 8) (*see* also **5.9.11.2**).

5.10.4 The direct-axis subtransient short-circuit time constant (τ''_{d}) is determined as the time required for the subtransient armature current component to decrease to $1/\epsilon \approx 0{\cdot}368$ of its initial value (*see* Fig. 7).

5.10.5 The armature short-circuit time constant (τ_{a}) is determined as the time required for the periodic component of the excitation (field) current (i_{f}) to decrease to $1/\epsilon \approx 0{\cdot}368$ of its initial current (*see* Fig. 11).

5.10.6 The armature short-circuit time constant (τ_{a}) from the decrease of the aperiodic armature current components in each phase is determined as the average time required for these components to decrease to $1/\epsilon \approx 0{\cdot}368$ of their initial value. Any phase whose initial aperiodic component is less than 40 percent of the initial resolved value shall be disregarded in determining the armature short-circuit time constant (*see* Fig. 9).

Determination of the armature short-circuit time constant from the decrease of the aperiodic armature current component is permissible, provided the armature current during sudden short-circuit test is measured by non-inductive shunts. The initial resolved value of the aperiodic current components is determined from the equation given below:

$$I_{\mathrm{dc}} = \sqrt{\frac{4}{27}\,(a^2+b^2-ab)} + \sqrt{\frac{4}{27}\,(a^2+c^2-ac)} + \sqrt{\frac{4}{27}\,(b^2+c^2+bc)}$$

where

a = largest value of direct-current component in the three-phase currents at the selected time, per unit;

b = second largest value of direct-current component per unit; and

c = smallest value of direct-current component per unit.

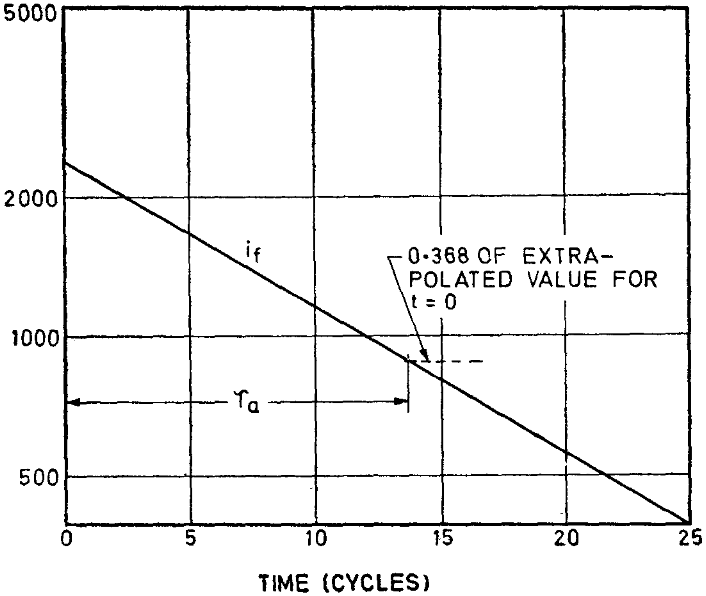


Fig. 11 Semilog Plot of ac Components (Crest Value) of Field Current i_f for Determination of Armature Time Constant τ_a

5.10.7 The largest possible instantaneous initial short-circuit current is determined as the sum of the values of periodic and aperiodic components at a half-cycle after the instant of the short-circuit.

The value of the periodic component at this instant is equal to the sum of the sustained, transient and subtransient components of the sudden short-circuit current.

The two latter components are taken directly from the diagram (*see* Fig. 7) for the corresponding instant.

The value of the aperiodic components is determined by the formula (in per unit or physical values) given below :

$$i_{\mathrm{a}} = i_{\mathrm{a\,max}}\, \epsilon^{\frac{-0{\cdot}5}{f\,\tau_{\mathrm{a}}}}$$

where

$i_{a\ max}$ = the largest possible value of the aperiodic current component of the sudden short-circuit determined in accordance with **5.9.13**,

ϵ = base of natural logarithm,

τ_a = the armature short-circuit time constant determined in accordance with **5.10.6**, and

f = frequency in hertz $\left(\frac{0{\cdot}5}{f}\text{ corresponds to a half-period}\right)$

5.11 Voltage Recovery Test

5.11.1 The voltage recovery test after disconnection of a sustained three-phase short-circuit is conducted on a machine running at rated speed with the armature winding short-circuited by a circuit-breaker at the beginning of the test.

The machine is operated with the armature winding short-circuited and with excitation current set at a value corresponding to the linear portion of the no-load saturation curve, which as a rule is not higher than 70 percent of rated open-circuit armature voltage, conditions being steady at the instant of operation of the circuit-breaker.

5.11.2 Quantities obtained from this test correspond to the unsaturated state of the machine. The requirements for the excitation system are the same as those given in **5.9.1**.

5.11.3 The sustained short-circuit shall be switched off practically simultaneously in all three phases with the currents being interrupted within 180 electrical degrees, or half a cycle. Oscillographic records (initial part at high speed) of one line voltage recovery and one armature current are required (*see* Fig. 12).

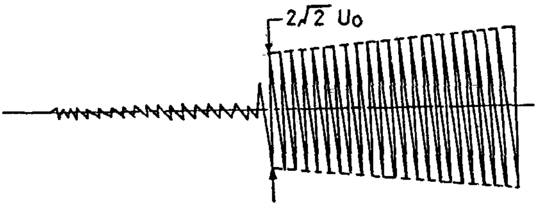


FIG. 12 OSCILLOGRAMS OF THREE-PHASE SHORT-CIRCUIT CURRENT BEFORE SWITCHING OFF AND RECOVERY VOLTAGE AFTER SWITCHING OFF

5.11.4 The difference between the sustained voltage and the voltage determined by the envelope of recovery voltage is plotted on a semilog scale against time, and extrapolated to the instant of the switching off of the short-circuit (*see* curve $\triangle u'$, Fig. 13).

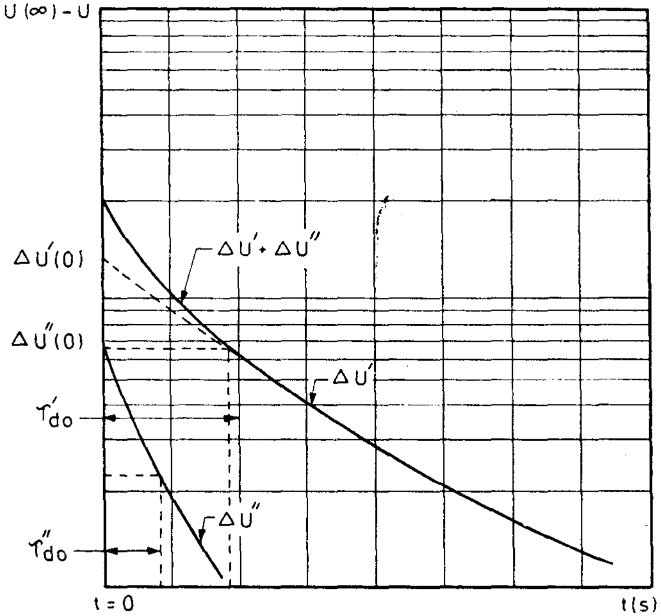


FIG. 13 REACTANCES AND TIME CONSTANTS FROM VOLTAGE RECOVERY TEST

The extrapolation of the straight portion of curve $\triangle u'$ to the ordinate gives the initial value of the transient voltage component $\triangle u'(0)$.

The difference between the voltage determined by curve $\triangle u'$ and the transient voltage component $(\triangle u')$ gives the subtransient voltage $(\triangle u'')$ for the corresponding instants.

5.12 Determination of Quantities from the Voltage Recovery Test

5.12.1 Direct-axis transient reactance is determined from the voltage recovery test as the ratio of the difference between the sustained voltage $u(\propto)$ and the initial value of the transient voltage component $\triangle u'(0)$ to the armature current (i_k) measured immediately before the disconnection of the short-circuit (*see* Fig. 13).

$$X'_d = \frac{U(\propto) - \triangle U'(0)}{\sqrt{3}\, I_k} \text{ ohms}$$

$$x'_d = \frac{u(\propto) - \triangle u'(0)}{i_k} \text{ per unit}$$

5.12.2 The direct-axis subtransient reactance is determined as the ratio of the difference between the sustained voltage $u(\infty)$ and the sum of the initial values of transient $\Delta u'(0)$ and subtransient $\Delta u''(0)$ voltage components of the armature current (i_k) measured immediately before the disconnection of the short-circuit (*see* Fig. 13).

$$X''_d = \frac{U(\infty) - [(\Delta U'(0) + \Delta U''(0)]}{\sqrt{3}\, I_k} \text{ ohms}$$

$$x''_d = \frac{u(\infty) - [\Delta u'(0) + \Delta u''(0)]}{i_k} \text{ per unit}$$

5.12.3 The direct-axis transient open-circuit time constant (τ'_{do}) is determined as the time required for the transient voltage component $\Delta u'$ to decrease to $1/\epsilon \approx 0{\cdot}368$ of its initial value (*see* Fig. 13).

The direct axis subtransient open-circuit time constant (τ''_{do}) is determined as the time required for the subtransient voltage component $\Delta u''$ to decrease to $1/\epsilon \approx 0{\cdot}368$ of its initial value (*see* Fig. 13).

5.13 Applied Voltage Test with the Rotor in Direct and Quadrature-Axis Positions with Respect to the Armature Winding Field Axis (*see* Fig. 14)

5.13.1 To conduct the test, ac voltage at rated frequency is applied to any two-line terminals of the armature winding.

The excitation winding shall be short-circuited. The duration of the voltage application shall be limited to avoid serious overheating of solid parts.

The rotor is slowly rotated to find the angular positions corresponding to the maximum and practically zero values of the excitation winding current. The first position corresponds to the direct-axis, the second to the quadrature-axis. Supply voltage, armature winding current and the power input are measured with the rotor stationary in these positions. Excitation winding current is determined for the purposes of evaluation of the rotor position (direct-axis or quadrature-axis), therefore, to measure it, the instrument need not necessarily be of high precision.

5.13.2 If it is not possible to perform the tests at the rated armature current or voltage, the determination of quantities referred to the unsaturated or saturated state of the machine shall be done from several tests with different supply voltages (20 to 70 percent U_n).

5.13.3 The quantities are plotted against applied voltage or armature current and the required values are found by extrapolation.

5.13.4 For machines with closed or semiclosed armature slots and closed damper winding slots, the supply voltage shall not be lower than 20 percent of the rated value.

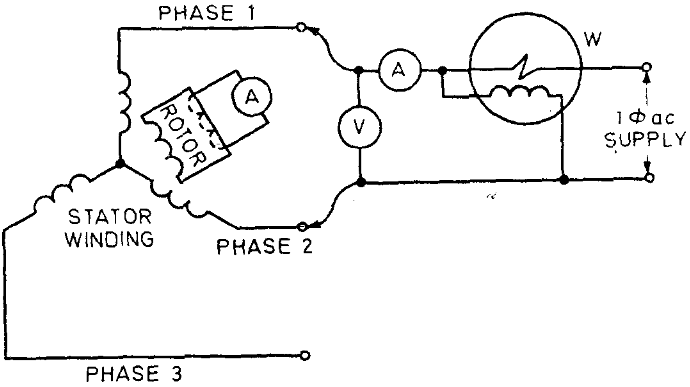


FIG. 14 DIAGRAM FOR DETERMINATION OF SUBTRANSIENT REACTANCES (BY APPLIED VOLTAGE TEST)

5.14 Determination of Quantities from the Test Described in 5.13

5.14.1 Direct-axis subtransient reactance from the applied voltage tests is determined using the formulae given below:

$$X''_d = \sqrt{Z''^2_d - R''^2_d} \text{ ohms}$$

$$x''_d = \sqrt{z''^2_d - r''^2_d} \text{ per unit}$$

where

$$Z''_d = \frac{U}{2\,I} \text{ ohms}$$

$$z''_d = \frac{\sqrt{3}}{2}\,\frac{u}{i} \text{ per unit}$$

$$R''_d = \frac{P}{2I^2} \text{ ohms}$$

$$r''_d = \frac{3}{2}\,\frac{p}{i^2} \text{ per unit}$$

The values of the voltage (U), current (I) and power input (P) are measured for the rotor position which gives the maximum excitation winding current.

5.14.2 Quadrature-axis subtransient reactance from the applied voltage test is determined using the formulae given in **5.14.1** where subscript d is replaced by subscript q. The voltage, current and power input are measured for the rotor position which gives practically zero excitation winding current.

5.15 Applied Voltage Test with the Rotor in Any Arbitrary Position — To conduct the test, ac voltage is applied in turn to each pair of the armature winding line terminals of the stationary machine under test.

The excitation winding shall be short-circuited. It is necessary that the rotor position remains the same for all three applications of test voltage.

If necessary the rotor shall be braked. The duration of the voltage application shall be limited so as to avoid serious overheating of solid parts.

The applied voltage, current and power input to the armature, and the excitation winding current are measured by applying ac supply voltage to each pair of the terminals.

Requirements for obtaining quantities referred to the unsaturated or saturated state of the machine are similar to **5.13**.

5.16 Determination of Quantities from the Applied Voltage Test with the Rotor in Any Arbitrary Position

5.16.1 Direct-axis subtransient reactance from the applied voltage test with the rotor in any arbitrary position is determined as given in **5.16.1.1** to **5.16.1.3**.

5.16.1.1 The reactances between each pair of the line terminals of the armature winding x_{12}, x_{23} and x_{31} are calculated from the formulae given in **5.14.1** (replacing subscript d by subscripts 12, 23 and 31, according to the terminals between which voltage is applied).

5.16.1.2 The direct-axis subtransient reactance is then calculated from the formula (in per unit or physical values):

$$x''_{\mathrm{d}} = x_{\mathrm{med}} \pm \Delta x$$

where

$$x_{\mathrm{med}} = \frac{x_{12} + x_{23} + x_{31}}{3}$$

$$\Delta x = \frac{2}{3} \sqrt{x_{12}(x_{12} - x_{23}) + x_{23}(x_{23} - x_{31}) + x_{31}(x_{31} - x_{12})}$$

5.16.1.3 The sign before Δx is determined from the following relations:

a) Plus (+), if the maximum of the three measured values of the excitation circuit current corresponds to the largest measured armature reactance between a pair of the armature winding line terminals.

b) Minus (—), if the maximum of the three measured current values of the excitation circuit corresponds to the smallest measured reactance between a pair of the armature winding line terminals.

5.16.2 Quadrature-axis subtransient reactance from the stationary impedance test with the rotor in any arbitrary position is determined similarly to the method described in **5.16.1**.

The sign before $\triangle x$ is determined from the following relations:

a) Plus (+), if the minimum of the three measured current values of the excitation circuit corresponds to the largest measured reactance between a pair of armature winding line terminals.

b) Minus (—), if the minimum of the three measured current values of the excitation circuit corresponds to the smallest measured armature reactance.

5.17 Test Conducted by Disconnecting the Machine Running Close to synchronous Speed from a Three-Phase Reduced Voltage Supply

The *D* and *Q* axes subtransient reactances are determined by disconnecting the machine, connected to the source of three-phase reduced (the rated voltage is also allowed) voltage rotating with a speed close to synchronous. The excitation winding should be short-circuited.

The voltage U_0, the armature current I_0 and the current in the excitation winding is oscillographed during test. The machine is disconnected from the source at the moment of maximum deviation of the ammeter connected to the excitation circuit. In this case the voltage instantly changes by value '$\triangle U_0$' (*see* Fig. 15) and thereafter uniformly alternates.

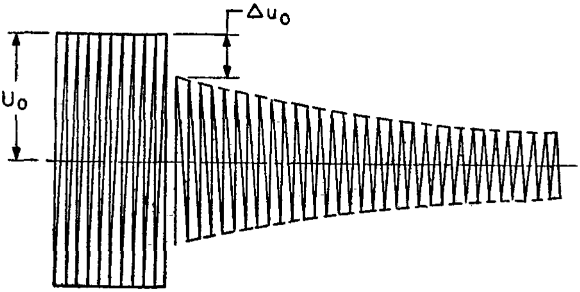


FIG. 15 OSCILLOGRAPH OF U_0

Subtransient reactance along the direct axis (X''_d) in per unit is calculated by formula:

$$X''_d = \frac{\triangle U''_0}{I_0}$$

where

$\triangle U''_0$ = instant change in U_0 in per unit, and

I_0 = armature current at the moment of disconnection of the machine in per unit.

If the machine is disconnected at a moment when the current in excitation winding is equal to zero, then the q axis subtransient reactance will be obtained similarly.

5.18 Line-to-Line Sustained Short-Circuit Test

5.18.1 To conduct the line-to-line sustained short-circuit test, any two line terminals are short-circuited (*see* Fig. 16) and the machine is driven at rated speed by some prime mover.

5.18.2 The short-circuit current (I_{k2}), excitation current and the voltage between the open line terminal and one of the short-circuited terminals are measured (U_{k2}).

To increase the accuracy of the measurements in the presence of voltage or current harmonics, the active (P) and reactive (Q) power should be measured.

The measurements are taken at several values of the short-circuit current.

5.18.3 To avoid serious overheating of solid parts, the duration of the line-to-line sustained short-circuit test at currents above 30 percent I_n should be limited to the time required for taking the readings of the instruments.

For salient pole machines the current may be increased up to the rated value, if the vibration of the machine does not exceed permissible values. For non-salient pole machines the armature current is usually limited to 50 percent of the rated value.

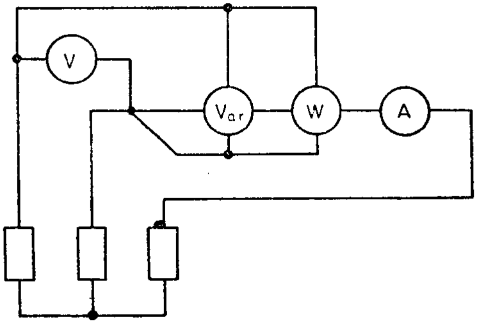


Fig. 16 Circuit for Line-to-Line Sustained Short-Circuit Test

5.19 Determination of Quantities from the Line-to-Line Sustained Short-Circuit Test

5.19.1 Negative sequence reactance from the line-to-line sustained short-circuit test is determined using the formulae given below :

a) $$X_2 = \frac{P}{\sqrt{3}\, I_{k_2}^2} \text{ ohms}$$

$$x_2 = \frac{p}{\sqrt{3}\, i_{k_2}^2} \text{ per unit}$$

These formulae apply when voltage or current harmonics may be ignored.

b) $$X_2 = \frac{U^2}{P}\left[\frac{P^2}{P^2 + Q^2}\right]\frac{1}{\sqrt{3}} \text{ ohms}$$

$$x_2 = \frac{u^2}{p}\left[\frac{p^2}{p^2+q^2}\right]\frac{1}{\sqrt{3}} \text{ per unit}$$

These formulae apply when the voltage or current harmonics shall be considered.

Negative sequence reactance is determined for each measured short-circuit current value. On the basis of the test data X_2 is plotted against current.

NOTE — The value of X_2 when the current equals $\sqrt{3}$ times the rated phase current will be taken as the rated current value.

5.19.2 Negative sequence resistance from the line-to-line sustained short-circuit test is determined using the formulae:

$$R_2 = \frac{U^2}{Q}\left[\frac{Q^2}{P^2 + Q^2}\right]\frac{1}{\sqrt{3}} \text{ ohms}$$

$$r_2 = \frac{u^2}{q}\left[\frac{q^2}{p^2 + q^2}\right]\frac{1}{\sqrt{3}} \text{ per unit}$$

Negative sequence resistance is determined for each measured short-circuit armature current. On the basis of the test data R_2 is plotted against armature current.

NOTE — The value of R_2 when the current equals $\sqrt{3}$ times the rated phase current will be taken as the rated current value.

5.20 Negative-Phase Sequence Test — The test is conducted when the reduced symmetrical voltage (2 to 20 percent U_n) is applied to a machine driven at rated speed connected to an external source of supply with negative-phase sequence, that is operating as an electro-magnetic brake with the slip equal to 2.

The excitation winding shall be short-circuited.

If the residual voltage of the machine under test exceeds 30 percent of the supply voltage, the rotor shall be demagnetized before testing the machine (*see* **5.5**). The voltage and current in all three phases and the supply power are measured during the test.

5.21 Determination of Quantities from the Negative-Phase Sequence Test — Negative sequence reactance and resistance are determined from the negative-phase sequence test by the formulae:

$$X_2 = \sqrt{Z_2^2 - R_2^2} \text{ ohms}$$

$$x_2 = \sqrt{z_2^2 - r_2^2} \text{ per unit}$$

$$Z_2 = \frac{U}{\sqrt{3}\,I} \text{ ohms}$$

$$z_2 = \frac{u}{i} \text{ per unit}$$

$$R_2 = \frac{P}{3I^2} \text{ ohms}$$

$$r_2 = \frac{p}{i^2} \text{ per unit}$$

where

U = average measured voltage applied,
I = average measured current, and
P = input power.

Negative sequence reactance and resistance are determined for each measured supply voltage. On the basis of the test data X_2 and R_2 are plotted against current.

5.22 Single-Phase Voltage Application Test — The test of single-phase voltage application across the terminals of the three-phase connected in series or in parallel is conducted with the machine driven at rated speed (*see* Fig. 17).

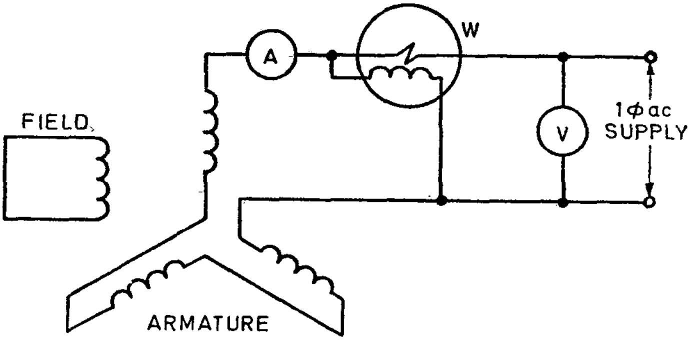
The connections should be arranged so that the current in the three phases at any instant should flow in the same sense, that is from neutral to line terminal or *vice versa* as defined by zero-sequence. The excitation winding is short-circuited.

Measurements are taken of the applied voltage, current and power input at several values of supply voltage. The values of the supplied voltage are chosen so that the armature winding current is of the order of the rated value.

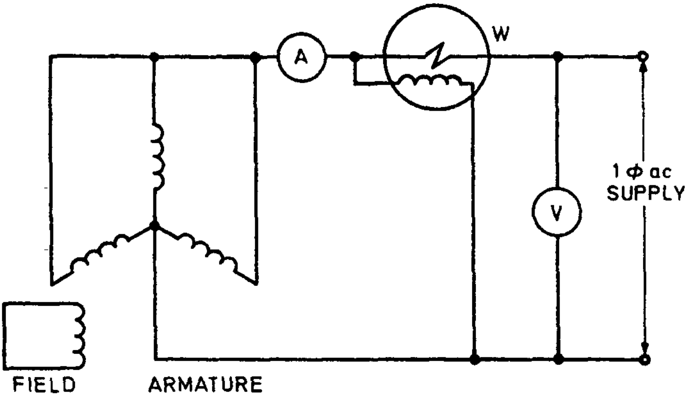
5.23 Determination of Quantities from the Single-Phase Voltage Application Test — The zero sequence reactance and resistance are determined from the test of single-phase voltage application across the terminals using the formula given below:

$$X_0 = \sqrt{Z_0^2 - R_0^2} \text{ ohms}$$

$$x_0 = \sqrt{z_0^2 - r_0^2} \text{ per unit}$$



17A Series Connection



17B Parallel Connection

FIG. 17 SINGLE-PHASE VOLTAGE APPLICATION TEST

When the three phases of the winding are connected in series :

$$Z_0 = \frac{U}{3I} \text{ ohms}$$

$$R_0 = \frac{P}{3I^2} \text{ ohms}$$

$$z_0 = \frac{1}{\sqrt{3}} \frac{u}{i}; \quad r_0 = \frac{p}{i^2} \text{ per unit}$$

When the three phases of the winding are connected in parallel:

$$Z_0 = \frac{3\,U}{I} \text{ ohms}$$

$$R_0 = \frac{3P}{I^2} \text{ ohms}$$

$$z_0 = 3\sqrt{3}\,\frac{u}{i}\ ; \ r_0 = \frac{9p}{i^2} \text{ per unit}$$

5.24 Line-to-Line and to Neutral Sustained Short-Circuit Test

5.24.1 To conduct the line-to-line and to neutral sustained short-circuit test the armature winding is star-connected, two line terminals are short-circuited to neutral, the machine is driven at rated speed and is excited (*see* Fig. 18).

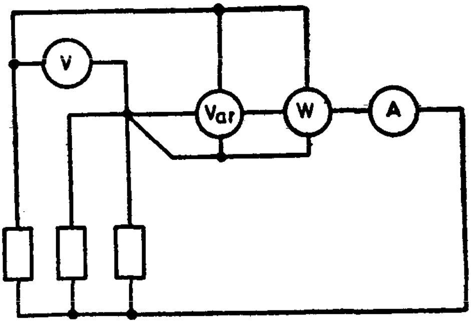


Fig. 18 Circuit for Line-to-Line and to Neutral Sustained Short-Circuit Test

5.24.2 Measurements are taken of the voltage from the open terminal to neutral (U_0) and the current in the connection from the short-circuited terminals to neutral (I_0).

5.24.3 To take into account the influence of harmonics, measurements are taken of active and reactive power.

5.24.4 The measurements are taken at several values of the neutral current. The current values and the duration of the test are limited by rotor over heating or vibration.

5.25 Determination of Quantities from the Line-to-Line and to Neutral Sustained Short-Circuit Test

5.25.1 The zero sequence reactance from the line-to-line and to neutral short-circuit test is determined by the formulae given below:

a) $$X_0 = \frac{U_0}{I_0} \text{ ohms}$$

$$x_0 = \frac{3\,u_0}{i_0} \text{ per unit}$$

These formulae apply when voltage or current harmonics may be ignored.

b) $$X_0 = \frac{U_0^2}{Q}\left[\frac{Q^2}{P^2 + Q^2}\right] \text{ ohms}$$

$$x_0 = \frac{u_0^2}{q}\left[\frac{q^2}{p^2 + q^2}\right] \text{ per unit}$$

Where U, P and Q are measured values of the voltage, active and reactive power respectively.

These formulae apply when the voltage or current harmonics shall be considered.

The zero-sequence reactance is calculated for several neutral current values. On the basis of the test data, X_0 is plotted against neutral current.

NOTE — The value of X_0, when the neutral current equals three times the rated phase current, will be taken as the rated current value.

5.25.2 The zero-sequence resistance from the line-to-line and to neutral short-circuit test is determined by the following formulae for several neutral current values:

$$R_0 = \frac{U_0^2}{P}\left[\frac{P^2}{P^2 + Q^2}\right] \text{ ohms}$$

$$r_0 = \frac{u_0^2}{p}\left[\frac{p^2}{p^2 + q^2}\right] \text{ per unit}$$

On the basis of the test data, R_0 is plotted against neutral current.

NOTE — The value of R_0, when the neutral current equals three times the rated phase current, will be taken as the rated current value.

5.26 Field Current Decay Test with the Armature Winding Open-Circuited

5.26.1 The field current decay test with the armature winding open is conducted with the machine driven by some prime mover at rated speed, excited to rated voltage, and suddenly short-circuiting the excitation winding. When necessary, the excitation winding supply source should be disconnected within 0·02 second.

5.26.1.1 When testing machines, a current limiting resistor may be connected in series with its excitation winding to limit the dc supply short-circuit current.

5.26.2 An oscillogram is taken of the armature winding voltage, the current in the excitation winding and the slip-ring voltage. The latter serves for precise determination of the instant of the starting of field current decay (zero time) and the determination of the initial voltage value at this moment.

The residual voltage is determined with the field winding open and with the machine operated at rated speed.

5.26.3 The difference between the transient voltage obtained from the oscillogram and the residual voltage of the machine is plotted against time on a semilog scale (*see* Fig. 19).

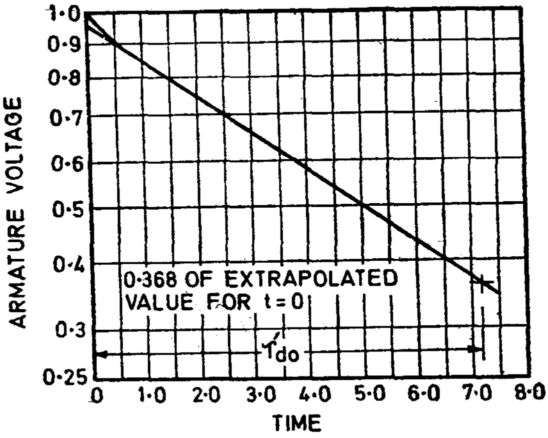


FIG. 19 DETERMINATION OF DIRECT-AXIS OPEN-CIRCUIT TIME CONSTANT

5.27 Determination of τ'_{do} from the Field Current Decay Test with the Armature Winding Open-Circuited — Direct-axis transient open-circuit time constant (τ'_{do}) is determined from the field current decay test as the time required for the voltage difference mentioned in **5.26.3** to decrease to $1/\epsilon \approx 0{\cdot}368$ of its initial value (*see* Fig. 19).

5.28 Field Current Decay Test with the Armature Winding Short-Circuited

5.28.1 The field current decay test with the armature winding short-circuited is conducted with the machine driven by a prime mover at rated speed and with rated armature current flowing, and suddenly short-circuiting the excitation winding. The limitation of the duration and the value of the supply source short-circuit current is made in accordance with **5.26**.

5.28.2 As oscillogram is taken of any line current and of the excitation current or slip-ring voltage.

5.28.3 The difference between the transient current obtained from the oscillogram and the sustained short-circuit armature current due to the residual voltage is plotted against time on a semilog scale.

5.29 Determination of τ'_d from the Field Current Decay Test with the Armature Winding Short-Circuited — Direct-axis transient short-circuit time constant (τ'_d) from the field decay test is determined as the time required for the current difference mentioned in **5.28.3** to decrease to $1/\epsilon \approx 0{\cdot}368$ of its initial value.

5.30 Suspended Rotor Oscillation Test

5.30.1 To perform this test, the rotor is suspended on one filament or two parallel filaments in such a way as to have its shaft in a vertical position. Turning the rotor produces oscillations about the shaft axis. The time required to make several oscillations is recorded and an average time of one cycle of oscillation is calculated.

5.30.2 With one filament suspension, the test is performed twice with the rotor itself and the rotor together with a flywheel or a pulley acting as a known flywheel.

5.30.3 The unidirectional displacement angle for one filament suspension should be not more than 45° and for two filament suspension not more than 10°.

5.31 Determination of τ_J and H from Suspended Rotor Oscillation Test — The acceleration time and stored energy constant from the string suspended rotor oscillation test are calculated using the formulae:

$$\tau_J = \frac{J\omega^2}{P_n} \cdot 10^{-3} \text{ seconds}$$

$$H = \frac{J\omega^2}{2S_n} \cdot 10^{-3} \text{ kWs/kVA}$$

where

J = moment of inertia in kgm^2,

$\omega = \frac{\pi n}{30}$ angular speed in rad/sec,

n = rated speed of rotation in rev/min,

P_n = rated active power in kW, and

S_n = rated apparent power in kVA.

The moment of inertia, when the rotor is suspended by one filament, is calculated using the formula:

$$J = J_p \frac{T^2}{T_p^2 - T^2} \text{ kgm}^2$$

and when it is suspended by two filaments, it is calculated using the formula:

$$J = \frac{T^2 a^2}{L} \cdot \frac{mg}{(4\pi)^2} \text{ kgm}^2$$

where

J_p = known moment of inertia of pulley in kgm²,
T = time of one cycle of rotor swing in seconds,
T_p = time of one cycle of rotor swing together with pulley or flywheel in seconds,
a = distance between the points of suspension in metres,
L = length of suspension in metres,
m = rotor mass in kilograms, and
g = acceleration of free fall in m/s².

5.32 Auxiliary Pendulum Swing Test

5.32.1 This test is recommended for machines provided with ball or roller bearings.

5.32.2 To perform this test, an auxiliary pendulum (a lever and a mass at the end) is attached in a plane at right angles to the shaft of machine, placed horizontally. The mass of the pendulum, which is known, shall be as small as possible. Instead of an auxiliary pendulum a known mass may be attached at the circumference of the rotor or pulley.

The auxiliary pendulum is displaced at an angle about 5° from its steady position. The time of one swing is measured.

5.33 Determination of τ_j and H from the Auxiliary Pendulum Swing Test — The acceleration time and stored energy constant from the auxiliary pendulum swing test are calculated by the formula as shown in **5.31**. The moment of inertia is calculated using the formula:

$$J = m_p L \left[\frac{T_p^2 g}{4\pi^2} - L\right] \text{kgm}^2$$

where

m_p = mass of the auxiliary pendulum in kilograms,
L = distance from the centre of the shaft to the centre of gravity of the pendulum or to the centre of gravity of the mass attached at circumference of rotor or pulley in metres,
T_p = time of one cycle of swing in seconds, and
g = acceleration of free fall in m/s².

5.34 No-Load Retardation Test

5.34.1 The no-load retardation test is conducted when there is no additional flywheel mass on the shaft of the machine under test. The machine is excited from a separate source and the excitation is unchanged during the test.

5.34.2 The machine under test is brought up to overspeed by increasing the supply frequency or by means of a prime mover provided with a clutch; then the supply is disconnected.

5.34.3 This test consists of measuring the retardation time $\triangle t$ when the machine is slowing down between two predetermined speeds with difference $\triangle \omega$, say, from 110 to 90 percent of rated speed or from 105 to 95 percent of rated speed.

In cases where overspeed is not permissible the retardation test is carried out at a speed close to the synchronous speed but below it.

5.35 Determination of τ_j and H from the No-Load Retardation Test

5.35.1 Acceleration time of the machine and stored energy constant from the no-load retardation test are determined using the formulae given below:

$$\tau_j = \omega_n \left(\frac{\triangle t}{\triangle \omega}\right) \left(\frac{P_{mech} + P_{Fe}}{P_n}\right) \text{ seconds}$$

$$H = \left(\frac{\omega_n}{2}\right) \left(\frac{\triangle t}{\triangle \omega}\right) \left(\frac{P_{mech} + P_{Fe}}{S_n}\right) \text{ kWs/kVA}$$

where

P_{mech} = mechanical losses at rated speed in kW determined according to IS : 4889-1968*,

P_{Fe} = core losses at rated speed and corresponding value of test voltage in kW determined according to IS : 4889-1968*,

P_n = rated active power in kW,

n = rated angular speed in rad/s,

S_n = rated apparent power in kVA, and

$\triangle t$ and $\triangle \omega$ are as defined in **5.34.3**.

5.36 On-Load Retardation Test of Mechanically Coupled Machines with the Synchronous Machine Operating as a Motor

5.36.1 The test is conducted with the machine operating as a motor and supplying a load. The speed of rotation of the unit before disconnecting from the network shall be equal to the rated speed.

The power input before disconnecting shall be not less than 60 percent of the rated power; the power factor shall be close to unity. The excitation of the machine during the test is unchanged.

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*Methods of determination of efficiency of rotating electrical machines.

After disconnecting the supply source, the change of speed of the unit during the first few seconds is determined.

5.36.2 The speed-time curve is plotted and a tangent to the initial point of curve is drawn. This tangent is used to determine the change in speed $\triangle \omega$ for the time interval $\triangle t$.

5.37 Determination of τ_j and H of Mechanically Coupled Machines from the On-Load Retardation Test with Synchronous Machine Operating as a Motor — The acceleration time and stored energy constant of the machine together with the load from the on-load retardation test with the machine operating as a motor are determined by the formulae given below:

$$\tau_j = \omega_n \frac{\triangle t}{\triangle \omega} \frac{P_1 - (P_{str} + P_{cu})}{P_n} \text{ seconds}$$

$$H = \frac{\omega_n}{2} \frac{\triangle t}{\triangle \omega} \frac{P_1 - (P_{str} + P_{cu})}{S_n} \text{ kWs/kVA}$$

where

P_1 = power supplied to the motor immediately before disconnection from the network in kW,

$P_{str} + P_{cu}$ = stray load losses+ohmic losses in armature winding immediately before disconnection in kW,

P_n = rated active power in kW,

S_n = rated apparent power in kVA, and

ω_n = rated angular speed in rad/s.

NOTE — This method of determination is not very precise.

5.38 Acceleration After a Load Drop Test with the Machine Operating as a Generator

5.38.1 The test is conducted with the machine operating as a generator driven by a prime mover.

5.38.2 Before the test, the generator load is fixed at 10 to 20 percent of the rated load (the power-factor is fixed close to unity), the speed regulator of the prime mover is taken out of service.

5.38.3 The excitation of the generator during the test shall be unchanged. After a sudden disconnection of the generator from the network the change of speed with time curve is determined. At a speed of about 107 to 110 percent of rated value, the regulation of prime mover is put in service or steam is cut off. The acceleration curve is plotted.

5.38.4 A tangent is drawn to the acceleration curve at the point corresponding to the rated speed of the machine, and the speed change for the time interval is determined.

5.39 Determination of τ_j and H of Mechanically Coupled Machines from the Acceleration After a Load Drop Test with the Machine Operating as a Generator — The acceleration time of the machine and its prime mover and stored energy constant from the acceleration after the load drop test with the machine operating as a generator are determined using the formulae given below:

$$\tau_j = \omega_n \frac{\Delta t}{\Delta \omega} \frac{P_1}{P_n} \text{ seconds}$$

$$H = \frac{\omega_n}{2} \frac{\Delta t}{\Delta \omega} \frac{P_1}{S_n} \text{ kWs/kVA}$$

where

P_1 = power supplied by the generator immediately before disconnection from the network in kW and other symbols denote the same as defined before,

P_n = rated active power in kW, and

S_n = rated apparent power in kVA.

NOTE — This method of determination is not very precise.

5.40 Determination of Quantities by Calculations Using Known Test Quantities

5.40.1 The quantities x'_d, x_d, τ'_{do} and τ'_d are connected with each other by the following relations:

$$x_d \tau'_d = x'_d \tau'_{do}$$

This relation is used for the determination of x'_d or τ'_d or τ'_{do} from the known values of x_d and two other quantities.

5.40.2 The negative sequence reactance from the known values of x''_d and x''_q is calculated by the formulae given below:

$$x_2 = \frac{x''_d + x''_q}{2}$$

5.40.3 The positive sequence resistance of the armature winding is determined from the known $3I^2_n R_a$ losses (P_{cu}) and stray losses in the armature winding (P_{str}) measured on three-phase steady short-circuit, at rated current in accordance with IS : 4889-1968* using the formulae given below:

$$R_1 = \frac{P_{cu} + P_{str}}{3 I_n^2} \text{ ohms}$$

$$r_1 = (P_{cu} + P_{str}) \text{ per unit}$$

This value of R_1 corresponds to the winding temperature at which the loss measurements were conducted.

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*Methods of determination of efficiency of rotating electrical machines.

5.40.4 Armature short-circuit time constant at rated frequency f_n from the known test values of saturated negative sequence reactance (x_2) and armature resistance per phase at 75°C (r_a) is calculated using the formula given below:

$$\tau_a = \frac{x_2}{2 \pi f_n r_a} \text{ seconds}$$

6. DETERMINATION OF RATED EXCITATION CURRENT

6.1 The rated excitation current of synchronous machine may be determined by any of the methods described in **6.2** to **6.5**.

6.2 Determination of Rated Excitation Current by Loading at Rated Conditions —The rated excitation current for rated armature current, power-factor and voltage may be obtained directly by loading the machine at the rated conditions and measuring the excitation current. This method is not generally applicable to the factory test, particularly in the case of large machines.

6.3 Determination of the Rated Excitation Current by Potier Diagram

6.3.1 To determine the rated excitation current by Potier diagram, use is made of the no-load saturation characteristic (*see* **5.1**), sustained short-circuit characteristic (*see* **5.1**) and Potier reactance X_p (*see* **5.2**).

6.3.2 The vector of the rated armature current (i_n) of the tested machine is laid off along the abscissa (*see* Fig. 20). The rated voltage vector (U_n) is drawn at the power-factor angle ϕ_n (which is considered to be positive for an overexcited generator) to it.

6.3.3 The vector of the voltage drop ($i_n x_p$) in the Potier reactance at the rated current is drawn from the end of the voltage vector as a perpendicular to the armature current vector. The voltage drop in the armature winding resistance is usually neglected. If necessary, it may be taken into account by drawing the vector of positive phase sequence voltage drop in the positive phase sequence armature winding resistance from the end of the voltage vector parallel to the current vector.

The vector should be laid off on the diagram (Fig. 20) in the direction of the armature current vector for generators and in the opposite direction for motors.

6.3.4 The vector sum of the rated voltage and the voltage drop in the reactance x_p gives emf vector e_p; the excitation current i_{fp} corresponding to this emf is determined from the no-load saturation curve and is laid off from the origin at 90° to the emf vector.

6.3.5 The excitation current component compensating armature reaction at rated armature current (i_{fa}) is determined as the difference between the

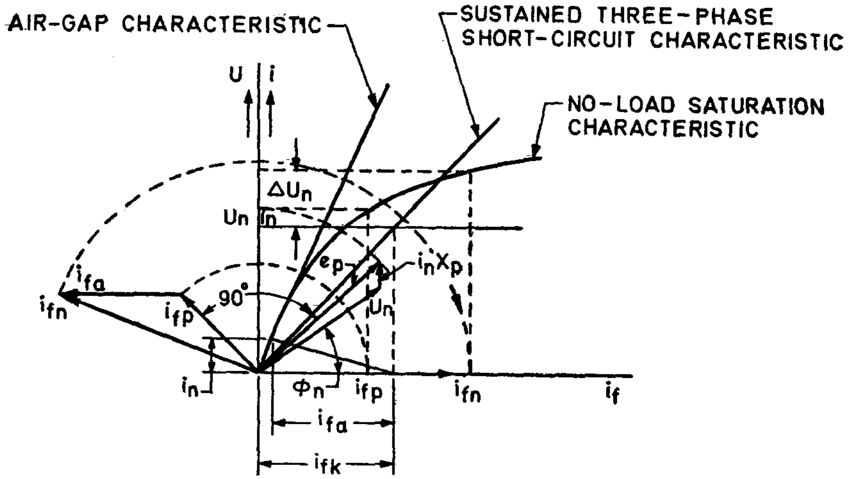
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FIG. 20 RATED LOAD EXCITATION FROM POTIER DIAGRAM

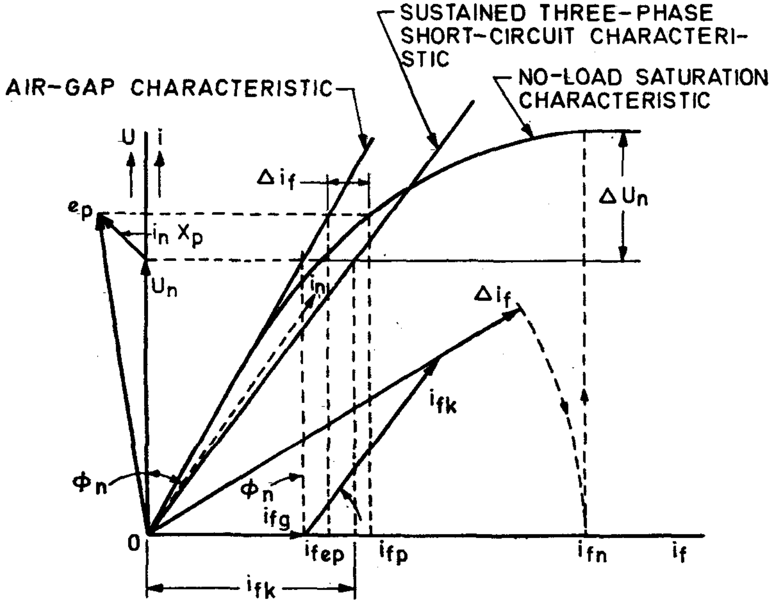
excitation current corresponding to the rated armature current on the sustained short-circuit characteristic, and the excitation current corresponding to the voltage drop in X_p due to armature rated current on the no-load saturation characteristic. Vector i_{fa} is laid off from the end of the vector i_{fp} parallel to the armature current vector. The rated excitation current i_{fn} is the vector sum of i_{fp} and i_{fa}.

6.4 Determination of the Rated Excitation Current by the ASA Diagram

6.4.1 To determine the rated excitation current of the machine by the ASA vector diagram (*see* Fig. 21), use is made of the no-load saturation characteristic (*see* **5.1**), the sustained three-phase short-circuit characteristic (*see* **5.1**) and the Potier reactance (*see* **5.2**).

6.4.2 The determination of emf e_p is made in accordance with **6.3**. The excitation current for the air-gap line at the rated armature voltage (i_{fg}) is determined from the no-load saturation characteristic. The vector current i_{fg} is laid off from the origin along the abscissa axis. From its end, at the rated power-factor angle ϕ_n (which is considered to be positive for an overexcited generator) to the right of the vertical, the vector of excitation current i_{fk} corresponding to rated armature current on the sustained three-phase short-circuit characteristic (*see* **5.2**) is laid off.

6.4.3 The vector current corresponding to the difference (Δi_f) between the excitation currents of the no-load saturation characteristic (i_{fp}) and on the air-gap line (i_{fep}), both for the voltage e_p (*see* Fig. 21) is laid off along the geometrical vector sum of the excitation currents. The sum of the three vectors corresponds to the rated excitation current.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NO-LOAD SATURATION CHARACTERISTIC
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FIG. 21 RATED LOAD EXCITATION FROM ASA DIAGRAM

6.4.4 The rated excitation current by ASA method may also be determined using the following equation (in per unit or physical values) :

$$i_{fn} = \Delta i_f + \sqrt{(i_{fg} + i_{fk} \text{ Sin } \phi_n)^2 + (i_{fk} \text{ Cos } \phi_n)^2}$$

6.5 Determination of the Rated Excitation Current by the Swedish Diagram

6.5.1 To determine rated excitation current of the machine by the Swedish diagram, use is made of the no-load saturation characteristic (*see* **5.1**), the sustained three-phase short-circuit characteristic (*see* **5.1**) and the excitation current corresponding to the rated voltage and armature current at zero power-factor (overexcited) (*see* **5.2.2**).

6.5.2 Three values of the excitation current are laid off on the abscissa axis (*see* Fig. 22A):

a) *OD* corresponding to the rated voltage on the no-load saturation curve,

b) *OB* corresponding to the rated voltage and armature current at zero power-factor, and

c) *OC* corresponding to the rated armature current on the sustained short-circuit characteristic.

6.5.3 If the excitation current at rated voltage, rated current and at zero power-factor overexcited is not available from the test, the same may be determined as given below while using the Swedish diagram.

Potier reactance X_p is computed according to **5.2.4** and the Potier reactance drop in X_p at rated armature current is added to the rated armature voltage (*see* point H' of Fig. 22B).

A line parallel to the abscissa axis is drawn from point H' to intersect with the open circuit characteristic in point H. From that point a perpendicular is drawn to intersect the abscissa axis at point J (*see* Fig. 22).

OC corresponds to the excitation current at rated armature current on the sustained short-circuit characteristic. *PC* (i_{fa}) corresponds to armature reaction effect, at rated current. Now to the right of the point J, the length *PC* is added along the axis to get the point B. The excitation current equal to the length of *OB* is the required current to be used in the Swedish diagram (*see* Fig. 22).

7. DETERMINATION OF THE PERCENTAGE INHERENT VOLTAGE REGULATION

7.1 Direct Method — The synchronous generator under test is loaded to its rated values of voltage, current, speed and power-factor. The excitation current under these conditions and the speed are kept constant and the load is gradually reduced to no-load condition. The terminal voltage E_0 of the armature is noted. The percentage inherent voltage regulation is calculated according to **7.3**.

7.2 Indirect Method — The rated excitation current is first determined according to **6.3**, **6.4** or **6.5** and the respective terminal voltage of the armature on open-circuit (E_0) is read from no-load saturation characteristic (*see* **5.1**). The percentage inherent voltage regulation is then calculated according to **7.3**.

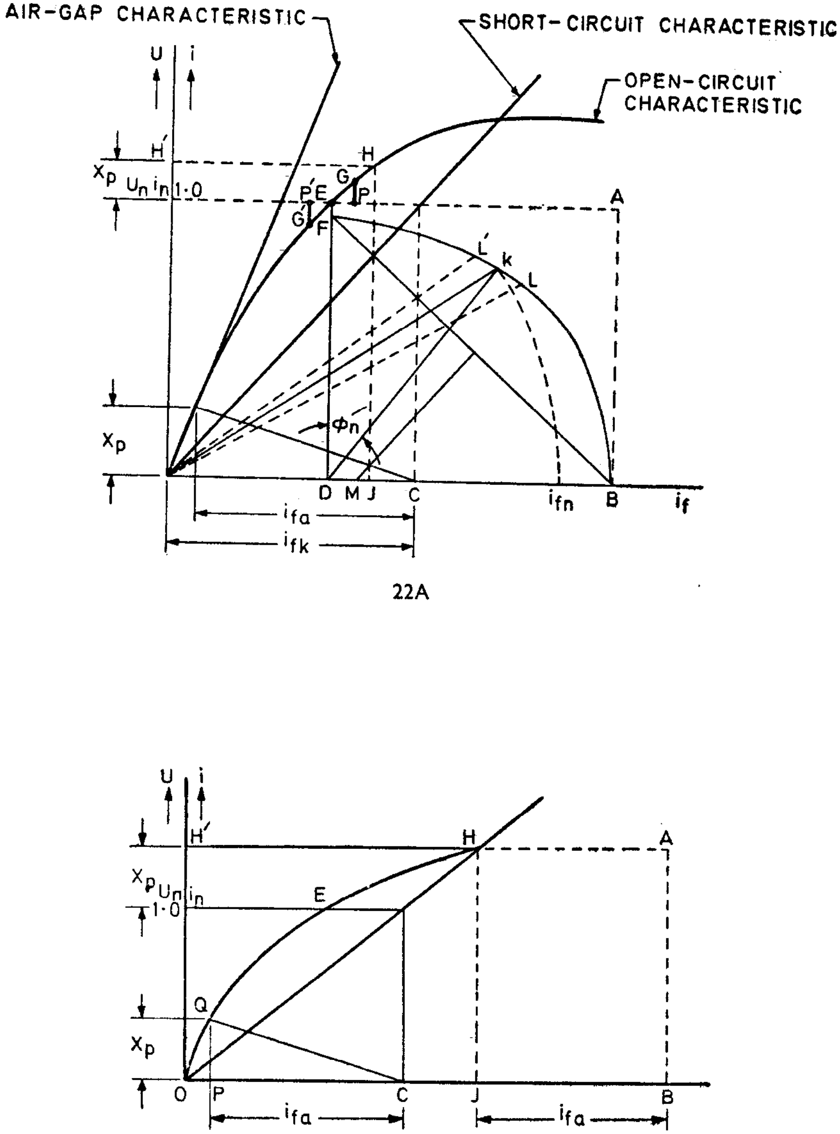
7.3 The percentage inherent voltage regulation is determined as given below:

$$\text{Percentage inherent voltage regulation} = \frac{E_0 - U_n}{U_n}$$

where

E_0 = armature terminal voltage on open-circuit corresponding to the rated excitation current, and

U_n = rated armature terminal voltage of the machine.



22A

22B

Fig. 22 Rated Excitation Current from Swedish Diagram

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